9

SUPERPOSED FOLDING IN THE BEECHWORTH CONTACT AUREOLE

By F. C. Beavis

Geology Department, University of Melbourne

Abstract

Analysis of the geometry and style of mesocopic structures developed in the hornfels of the Beechworth contact aureole suggest three periods of folding on the west flank of the North East Victorian Metamorphic complex. A microscopic form of rodding structure, developed in B2 folds, and deformed by the B3 folding, is described.

Introduction

A recent note (Beavis 1963) recorded evidence of at least two periods of folding in Ordovician slates near Mitta Mitta, on the E. margin of the Metamorphic Complex of North East Victoria. Evidence of three periods of folding, in beds of approximately the same age as those at Mitta Mitta, has now been obtained near Beechworth, on the W. flank of the Complex. Between Myrtleford and Beechworth the evidence of multiple deformation is abundant, but the advanced weathering and poor exposures over much of the area make detailed regional analysis almost impossible. In the contact aureole between the Murmungee Basin and Beechworth granites, however, some small but excellent exposures of fresh pelitic hornfelses occur. The study reported in this paper was restricted to one such exposure on the Lower Three Mile Ck. Because of the restriction, conclusions drawn from the study may not be generally applicable; they are intended to serve as a basis for the extension of the studies by others currently working in the area.

The folds of the first phase (B1 folds) are relatively large similar types, comparatively tight, with hinges spaced at intervals varying between 1 to 20 chains. Samples for detailed analysis were selected from a limb of one of these folds, at which scale the B1 folds are represented only as lineations (L_1). The samples show the lineations, L_1, L_2, L_3, of the three deformations; bedding S; and the strain slip cleavages S_2' and S_3' imposed during the second and third folding respectively. Any cleavage developed during the first deformation is not visible mesoscopically at the locality studied, but can be observed in metapelites elsewhere in the area. The B2 and B3 folds are strongly developed, but are rarely greater than 10 cm in size.

The writer acknowledges with gratitude the help received from the following:

Mr M. D. Leggo, of the University of Melbourne, who made available some of the samples studied, and prepared both Fig. 1 and the locality geology for this paper; and Mrs F. C. Beavis and Miss Elizabeth Carroll who assisted with the preparation of the figures.

Locality Geology

(By M. D. Leggo)

The locality examined, and from which the samples for detailed analysis were obtained, is situated on the Lower Three Mile Ck, ¾ mile below the junction of this stream with Two Mile Ck, and 2¾ miles SSW. of Beechworth township. The locality lies in a composite contact metamorphic aureole associated with the main Beechworth granite, an adamellite intrusion at the SW. of this granite, and the Murmungee Basin granite. The age of the parent sediments is not known with certainty since the nearest recorded fossils occur at Myrtleford, 15 miles S. of Beechworth, where Hall (1908) recorded *Dicellograptus*. The sediments consist of thin, finely laminated shales, alternating with thicker greywackes and occasional beds

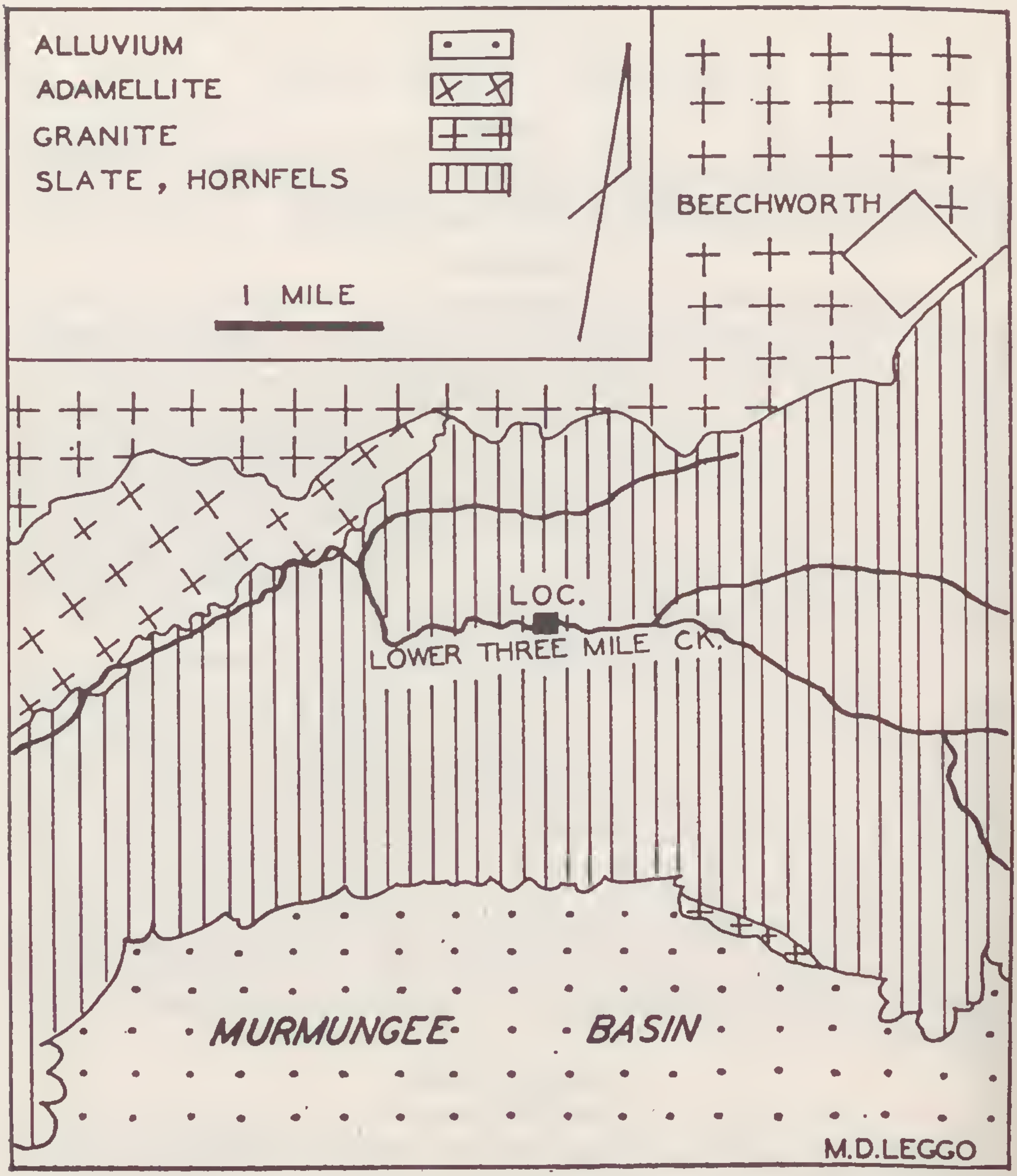

FIG. 1—Locality Map.

of grit. The strike of the bedding between Myrtleford and Beechworth varies between N.40° W. and N.10° W. Dips are steeply E., or more usually, W.

In thin section, the hornfels from the locality under discussion, is seen to consist of alterating bands of pelite and psammopelite with respective thicknesses of 1 mm and 2 mm. The differences between the two types are marked: the pelitic bands are conspicuously iron stained with less quartz and more mica than the psammopelitic bands.

The pelitic bands consist chiefly of mica, with muscovite predominating: the muscovite flakes are well developed, and have a larger size than the other minerals. Trains of sericite shreds, and a pleochroic colourless to light dirty green mica are also present. Quartz, chlorite, and opaque grains are the other main constituents. Yellow-brown iron oxide stains are pronounced.

The psammopelitic beds are composed mainly of strained quartz: the quartz has bubble-like inclusions. Shreds of sericite and small flakes of colourless to light brown pleochroic biotites are present. Felspar and opaque grains are minor constituents.

Structural Analysis

Mesoscopic Analysis

Folding of the first (B1) phase:

The B1 folding which, from mesoscopic field observations had a style combining both parallel and similar elements, involved a foliation, S, formed by fine alternating dark and light bands 1 to 2 mm thick. This foliation represents a primary lamination emphasized by mimetic recrystallization during contact metamorphism. The lineation, L_1, developed on S during the B1 deformation, is represented by fine wrinkles or plications of S. The subsequent deformation of L_1 makes the determination of its general orientation difficult, but it seems to plunge very steeply to the S.

At and near the locality studied, axial plane cleavage (S_1') of this stage is not visible mesoscopically. This seems to be a feature of the area generally, S_1' being observed only very locally. The pelitic sediments involved in the B1 folding show the geometry of similar folds, but shear does not appear to have been a mechanism of significance in their deformation.

Folding of the second (B2) phase:

Since B2 structures have been deformed by the B3 folds, analysis was possible only by dividing the samples studied into domains in which the B2 folds were cylindrical and in which the axial surfaces, S_2', and axes, L_2, of these folds, displayed orientation homogeneity. The B2 folds are small antiforms and synforms, with rounded hinges; individual folds are rarely larger than 5 cm. These folds have developed in zones 12 to 25 cm wide, between which S remained planar during this phase. The axial surfaces are defined by a strain slip cleavage; the style of the folding is 'similar' and shear seems to have been the dominant mechanism. Profiles of these folds are illustrated by Fig. 2a.

The lineation, L_2, formed during B2, is defined by the hinges of the folds and by the intersection of S and S_2'. While L_2 is rectilinear over domains in which the B2 folds are cylindrical, the B3 deformation has produced an overall curvilinear form for L_2.

The analysis of B2 folds for two domains in which these folds are cylindrical, i.e. domains bounded by axial surfaces of B3 folds, is shown in Fig. 2b and 2c. For field A, the axial surfaces S_2' dip steeply SE. and strike north easterly. The fold axes, L_2, plunge 80° S. This field has apparent monoclinic symmetry. The

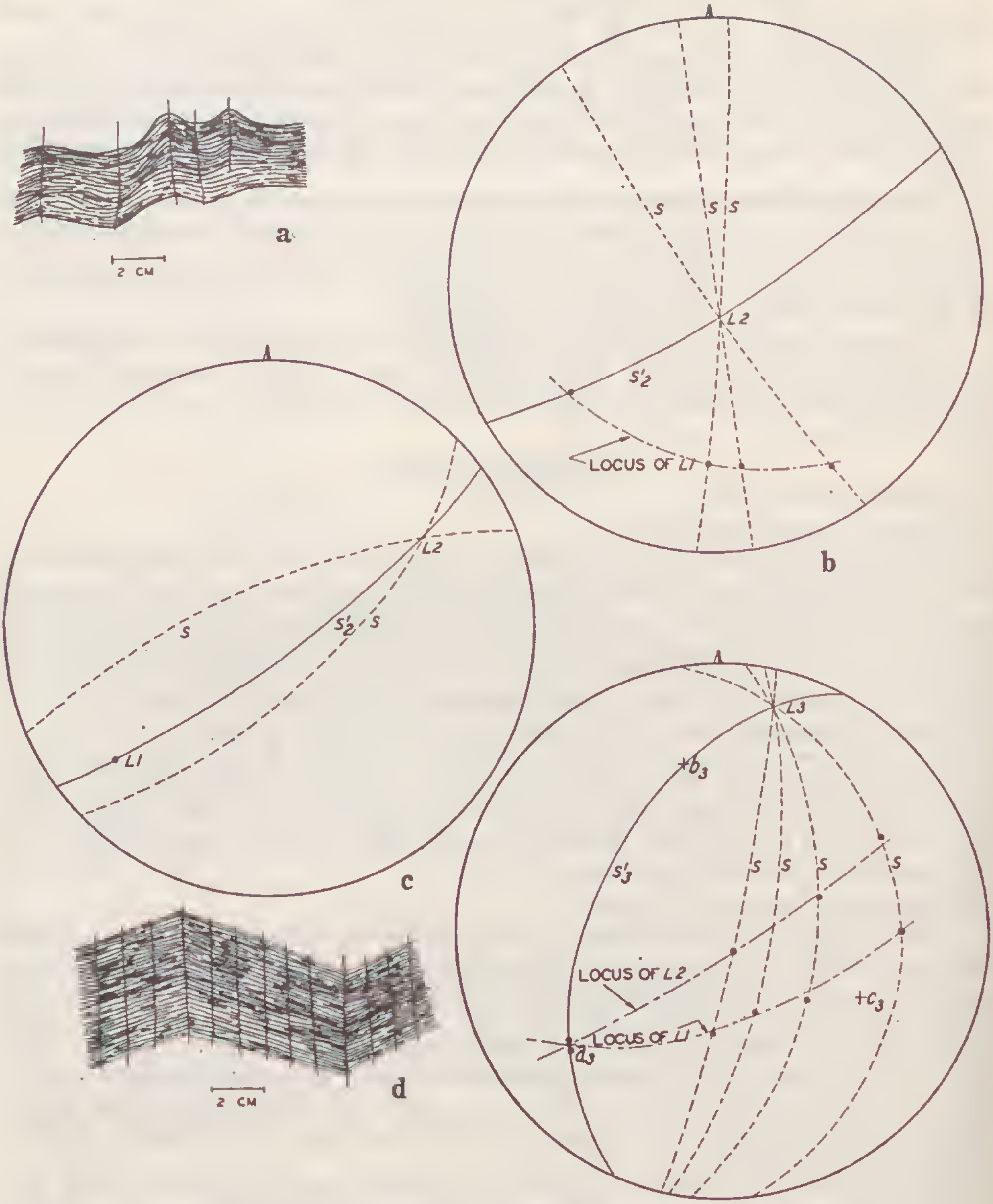

FIG. 2—Mesoscopic geometry of B2 and B3 folds.

a. Profile of B2 folds.
b. Analysis of B2 folds, field A.
c. Analysis of B2 folds, field B.
d. Profile of B3 folds.
e. Analysis of B3 folds.

orientation of L_1, deformed during the B2 phase, measured on limbs and hinges of the B2 folds, make angles with L_2 ranging between 49° and 62°, and lie on a great circle of the projection. Using the criteria of Ramsay (1960), these data support the observation that B2 folding was by a mechanism of shear.

The intersection of the locus of L_1 and the axial surfaces S_2' defines the direction of movement, i.e. the *a* tectonic axis of the B2 folding. Because of the B3 deformations, however, the orientation of *a*2 is apparent only, and, because of the uncertainty regarding the attitudes of S before B3, 'unrolling' about L_3 may not give the true orientation of *a*2.

Within field B, the axial surface S_2' shows a rotation with respect to its orientation in field A, while the folds themselves plunge to the NE. In this field, no sample showed a sufficiently clear definition of L_1 on B2 folds for the study of the deformation of the former to be attempted with any degree of confidence in the result.

Folding of the third (B3) phase:

Whereas the B2 folds are rounded, relatively appressed types, the B3 folds have a different style; they are broad, open, chevron-like antiforms and synforms, the hinges of the folds being spaced regularly at intervals of about 5 cm. The profile of these folds is shown in Fig. 2d. The axial surfaces, S_3', are planes of strain slip cleavage; these planes are spaced at 1 to 1·5 cm but are restricted to the hinges and, in some cases, one set of limbs. The lineation, L_3, is formed by the intersection of S and S_3' and of S_2' and S_3'. It is marked by ridges, 2 mm high, on S. This, again, is a contrast in style to the B2 folds, where S_2' was restricted to the actual axial planes. S_3' dips 50° WNW. and strikes NNE. L_3 plunges 12° in the direction N.16° E.

On the limbs and hinges of the B3 folds L_1 and L_2, deformed by the B3 phase, can be observed. These have been plotted in Fig. 2e. The loci of both sets lie on great circles of the projection: the angles which each makes with L_3 vary. For L_2, these are 45°, 82°, 122°, and for L_1, 70°, 93°, 100°, 108° and 122°. The geometry, then, confirms the mesoscopic data suggesting slip on cleavage planes as the mechanism of B3 fold development.

The loci of both L_1 and L_2 intersect S_3' in *a*3, the direction of movement in the B3 deformation. The *b*3 tectonic axis, which lies in S_3' can be found by construction. It will be noted that *b*3 and L_3 are not coincident. The B3 folds have been formed by slip on strain slip cleavage (*a*3 *b*3), and bedding planes. Hence, both from the structural and analytical viewpoints, these planes are of considerably greater significance than the fold axes which lie in these planes. This aspect becomes most important when, as in the case of the B3 deformation, the folds have developed in a surface with varying attitudes.

Microscopic Analysis

As stated above, the B1 deformation is represented in the samples by the mesoscopic L_1 and S. The latter appears in thin section as alternating quartz rich and mica rich laminae. For this study, thin sections were cut in two planes: one subnormal to L_2, the other subnormal to L_3. These sections show arrays of quartz domains not visible mesoscopically. The domains, which are restricted to the quartz-rich laminae, terminate abruptly against the micaceous laminae in the section $\perp L_3$. In the $\perp L_2$ section, the quartz domains lie parallel to S, and are restricted to the hinge zones of the B2 folds. In the $\perp L_3$ section, the domains lie *en echelon* in the plane of S_3' (Fig. 3a) while the long axes lie in S_2'. The domains are clearly linear structures on a microscopic scale, formed in the B2 folds parallel to L_2 and which were deformed by the B3 phase. They may be compared to the 'rodding structures' of Wilson (1953) but, because of their small size, some distinction should be drawn, and the term 'spindle structure' is suggested. Since these structures are restricted to the quartz-rich bands, it seems likely that they formed by segregation of quartz during the B2 folding. Kinking of the spindle structures where they abut on the micaceous bands argues some slip on S during the B3 folding (Fig. 3c).

FIG. 3—Spindle structures in hornfels.

a. Spindle structures in $\perp L_3$ section, prepared from composite photomicrograph.
b. Spindle structures in $\perp L_2$ section, prepared from composite photomicrograph.
c. Details of spindle structures in $\perp L_3$ section.

Analysis of [0001] quartz orientation has been made with two aims: one, to confirm the deformation of the spindle structures, the other, to attempt an assessment of the effects, if any, on the microfabric, of the B1 deformation.

Fig. 4a shows the [0001] orientation of quartz crystals which constitute the spindle structures: two partial girdles have been developed, one in S_2', the other in S_3'. The 7% maximum in the latter girdle is coincident with L_3, while the 4% maximum which lies in the S_2' girdle is coincident with L_2 in this field. Clearly, both B1 and B2 influenced the orientation of the quartz in the spindle structures.

The orientation of the matrix quartz (Fig. 4b) is more complex, as would be anticipated. Again, the strongest concentration of [0001] is in L_3, with the two partial girdles in S_2' and S_3'. There is, additionally, evidence of a third girdle containing three maxima (4%, 5%, 7%); the question arises as to whether or not this girdle represents S_1', the axial surface of B1 folds, not visible mesoscopically. Support for this idea is gained from the fact that the trend of this girdle approximates to that of the intersection of the plane containing the deformed L_1 and the plane of the thin section.

FIG. 4—Microscopic Analysis of Hornfels.

a. 193 [0001] quartz in spindle structure section ⊥ L_3.
   Contours 7 – 6 – 5 – 4 – 3 – 2 – 1%.
b. 271 [0001] quartz in quartz-rich bands (matrix) of hornfels. Section ⊥ L_3.
   Contours 10 – 9 – 8 – 4 – 3 – 2 – 1%.

Discussion

Bryhni (1962) stated that the distinction between different tectonic phases on the sole basis of differently oriented fold axes may not always be justified since one set of movements might be able to form linear structures of highly variable trend. It is not so much the trends of lineations which indicate more than one phase of folding '. . . it is rather the style of folding and the geometric harmony between structures of the same style'. A similar idea has been expressed by Ramsay (op. cit.). The tendency in recent years has been to concentrate purely on the geometric analysis of the structural elements, without adequate regard to the style of the elements themselves. In the present case, the geometric analysis certainly indicates three periods of folding. The B1 folds apparently developed by flexure, slip on S, and flow, without significant slip on cleavage planes. That some slip on cleavage S_1' did occur is suggested by the microscopic data. The B2 folds have a 'similar' style, and were developed by slip on cleavage planes which form the axial surfaces of these folds. Folding during the third deformation was again by slip on cleavage planes, although there is microscopic evidence of slip on S. These B3 folds have a chevron style, and, as previously noted, the cleavage planes are more highly developed and more closely spaced than the comparable B2 structures. There is a strong concordance of the geometry of the structures of the same style.

Initial deformation of the Upper Ordovician sediments from which the schists of the metamorphic complex were derived occurred during the epi-Ordovician Benambran Orogeny. Where the structure of the complex has been studied in detail, it has been found that the post-Benambran orogenies imposed discrete fault and joint structures, but not folds, on the schists. It has been concluded that, by the time the Bowning and Tabberabberan Orogenies were effective, the rocks of the complex were in such a tectonic environment and in such a physical condition that strain could only be expressed by discrete fracturing (Beavis 1962).

This leads to the idea that the superposed folding observed in slates and hornfelses on the flanks of the complex is not necessarily to be regarded as the result of more than one orogeny. Rather, it may be considered the result of separate phases of movement during the same orogeny. By virtue of the constantly changing environment and physical condition of the rocks, as well as the imposition of penetrative heterogeneities, and hence the varying orientation and intensity of the principal stresses, small folds of varying style and geometry could be imposed on the earlier major folds.

References

Beavis, F. C., 1962. The geology of the Kiewa Area. *Proc. Roy. Soc. Vict.* 75: 349-410.

————, 1963. Superposed folds in the Metamorphic Complex, North East Victoria. *Aust. J. Sci.* 26: 23-24.

Bryhni, I., 1962. Structural analysis of the Gr neheia area. *Norsk. Geol. Tidss.* 42: 331-371.

Hall, T. S., 1908. Report on graptolites. *Rec. Geol. Surv. Vict.* 2: 221.

Ramsay, J. G., 1960. The deformation of early linear structures. *J. Geol.* 68: 75-93.

Wilson, G., 1953. Mullion and rodding structures in the Moine Series of Scotland. *Proc. Geol. Assoc., London* 64: 118-151.